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A Literature Review

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The mining, milling, and processing of mineral resources may cause varying degrees of technologically enhanced natural radioactivity (TENR) which is dependent on the inherent uranium and thorium content of the target resource and the details of the total extraction process.

The objective of this review is to identify from the available domestic literature possible metallic and nonmetallic mineral extraction industries (exclusive of uranium, phosphate, and fossil fuels) which may require subsequent assessment. Certain industries such as phosphate and coal are already identified as potential sources of radioactivity; hence, they are excluded from this overview.

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RADIOACTIVITY IN SELECTED MINERAL EXTRACTION INDUSTRIES
A LITERATURE REVIEW

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November 1978

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PREFACE

The Office of Radiation Programs of the Environmental Protection Agency carries out a national program designed to evaluate population exposure to ionizing and non-ionizing radiation, and to promote development of controls necessary to protect the public health and safety. This literature survey was undertaken to identify possible sources of ionizing radiation in the mineral extraction industries (excluding uranium and phosphate). The information gathered during the survey is also serving as a guide in planning further studies to meet the requirements of the Clean Air Act (as amended in 1977). Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

Donald W. Hendricks
Director, Office of
Radiation Programs, LVF

ABSTRACT

The mining, milling, and processing of mineral resources may cause varying degrees of technologically enhanced natural radioactivity (TENR) which is dependent on the inherent uranium and thorium content of the target resource and the details of the total extraction process.

The objective of this review is to identify from the available domestic literature possible metallic and nonmetallic mineral extraction industries (exclusive of uranium, phosphate, and fossil fuels) which may require subsequent assessment. Certain industries such as phosphate and coal are already identified as potential sources of radioactivity; hence, they are excluded from this overview.

Uranium and thorium content is a useful first order measure of the radioactivity a mineral commodity may contain. This, in turn, is dependent on the gross geochemical characteristics and geological history of the ore body of concern. The observed variability of uranium and thorium content is dependent not only on mineral genesis but also on the local geological setting. This along with the absence of many direct observations prevents confident selection of mineral commodities with consistently large TENR. However, the following metallic commodities should be subject to further exploratory inspection: rare-earth elements, gold, iron, molybdenum, copper, aluminum, and lead-zinc. Among these, mining and milling of molybdenum and gold ores have been associated with the largest radiation levels in air and water, respectively. Placer deposits of any metal should be inspected for radiation

related to the thorium decay chain. Similarly, resources which are the residual results of weathering should be evaluated. Nonmetal resources which appear to have the greatest potential of TENR are fluorspar, granite, and clays. Underground operations in most any material may have elevated radioactivity as is the case for caves in limestone, which consistently is among the rocks having the lowest associated radioactivity. Radiation surveys should involve the uranium and thorium decay chains and other naturally occurring radioisotopes as applicable. Secondly, each operation should be surveyed, restricting generalizations to the same geological province and to deposits with similar local geology, mineralogy, and genesis.

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INTRODUCTION

In order to establish radiation protection guidance, the Office of Radiation Programs (ORP) of the U. S. Environmental Protection Agency (USEPA) makes a continuing effort to identify source categories of radiation. An area of increasing interest involves the identification of enhanced human exposure to ambient radiation and radioactive material resulting from various human activities that concentrate or redistribute radioactive material in the earth's crust.

This brief review is intended as an overview document which will support ORP efforts under the Clean Air Act as amended in 1977. This review is not to be considered inclusive and primarily will address readily available domestic literature only. Secondly, a substantial amount of current information germane to this report on uranium and thorium concentrations in various geological materials is unpublished. Some of the observations given herein are admittedly dated but are included for lack of more recent information. This report primarily provides some background information on which further investigative activities can be based.

Of the approximately one hundred naturally occurring radionuclides, about thirty (most of which are members of the uranium and thorium decay series) are of interest due to their abundance and toxicity (Conference of Radiation

Control Program Directors, 1977). Natural radiation is by far the largest source of human radiation exposure to the world population (United Nations Scientific Committee on the Effects of Atomic Radiation, 1977). The major portion of this exposure is unavoidable. However, as a result of industrial activities and changes in modes of living due to technological advances, increased exposures to naturally occurring radioactive materials can take place. This process has been designated as "Technologically Enhanced Natural Radiation" or TENR (Gesell and Prichard, 1975).

Extraction and processing of mineral commodities may enhance exposure of humans to natural radioactivity in several ways. Workers located in or adjacent to mining sites can be exposed to gamma radiation from the ore body as well as the surrounding rocks. Exhalation of radon gas from exposed surfaces can result in an inhalation hazard to mine workers, particularly in underground operations. Beneficiation, involving such operations as grinding, washing, flotation, drying, or chemical extraction, can redistribute or concentrate radioactive material in tailings, byproducts, products, or wastes. Tailings may become a hazard if used in construction or reclamation. Waste water may contaminate surface water or find its way into ground water. Potable water supplies may be contaminated and result in radiation exposure to users. If radioisotopes are concentrated in a product or byproduct, exposure can result when this material is fabricated into a consumer product and ultimately located in close proximity to humans in either the home or work place. However, this facet is not within the scope of the study presented herein.

Occupational and public radiation exposures as a result of uranium mining and milling have been documented and were initially investigated in this country in the early 1950's. Studies of radiation exposure associated with certain phosphate mining and processing operations have been conducted by Spalding (1972), Guimond and Windham (1975), and the U. S. Environmental Protection Agency (1973). In many respects, exposure to elevated levels of radioactivity as a result of phosphate extraction has occurred in a manner similar to that from uranium extraction. Exposure can occur via inhalation of radon gas and its radioactive decay products in enclosed areas (USEPA, 1975), direct exposure to gamma radiation from solid waste and byproduct material (Duncan et al., 1977), and ingestion of water from supplies which have elevated radioactivity (Kaufmann and Bliss, 1977).

These and other findings have led to this attempt to identify potential sources of radiation exposure resulting from mineral commodity extraction and production operations. As a first step, the present study attempts to indicate, through an examination of the domestic literature, those minerals which may be expected to be associated with increased concentrations of naturally occurring radioactivity. Emphasis is on resource development (mining, processing) rather than on product or byproduct use by the consumer.

GEOCHEMISTRY OF URANIUM AND THORIUM

INTRODUCTION

The movement of uranium, thorium, and associated elements in the earth is part of a natural geochemical cycle between rock, water, and air. While human dose assessment is one of the ultimate concerns, the understanding of the enrichment processes of radioactive elements in the lithosphere has direct application in defining extractive mineral ore bodies which may show preferential enrichment in radioactivity.

The behavior of uranium and thorium is dependent on the outer electron configuration. For example, thorium is analogous to the rare-earth elements, with an incomplete 5f shell. A valence state of 4^+ is dominant with 3^+ or 2^+ states occasionally noted. Only the tetravalent state is observed for thorium under natural surface conditions. In general, thorium compounds exhibit low solubility. The thorium ion in solution is small, highly-charged, and forms an extensive number of complexes (Ames and Rai, 1978). In the tetravalent state the ionic radius is similar to U^+ and Ce^+.

Uranium has been identified as forming about 103 distinct minerals. Uraninite is the most commonly identified ore mineral. Many secondary minerals can be formed including sulfates, silicates, phosphates, molybdates,

and vanadates as well as multiple oxides (Ames and Rai, 1978). Generally, the geochemistry of uranium is intimately associated with thorium, particularly in the distribution in igneous rocks. However, significant separation between the two elements does occur during weathering, transport, and deposition in the sedimentary cycle (Rogers and Adams, 1969b).

The overall similarity in size, electron configuration, and bonding nature of thorium, cerium, uranium, and zirconium promotes geochemical association with various other elements (Bayer, 1974). These associations provide valuable keys to defining possible ores and products or byproducts wherein there is enrichment of radioactive elements. Many observed elemental assemblages can be predicted by noting similarity in outer electron configurations and other relevant properties as noted above.

Two broad processes whereby radioactive elements relate to the geochemical cycle include igneous differentiation and sedimentary deposition. Both processes can cause reconcentration of radioactive elements. For igneous rocks, differentiation by fractional crystallization of magma is one of the primary processes for partitioning elements. Certain late crystallizing minerals, e.g., potassium and sodium feldspars and quartz, may be enriched in trace elements (including uranium and thorium) due in part to their increased concentration in the magma from which these minerals crystallize. Secondly, gases and fluids expelled from cooling magmas are thought to be responsible for the formation of many metallic ore deposits, particularly those of hydrothermal origin. Occasionally, surface or ground water remobilizes uranium and other metals and redeposits them as secondary minerals or secondary ore deposits. Other concentrating mechanisms occur in the

sedimentary cycle and particularly involve minerals containing thorium. Many of these minerals are resistates, i.e., minerals resistant to chemical and physical weathering, as well as being characterized by high specific gravity. Because of these properties, thorium minerals, when introduced into dynamic water bodies, may form placer deposits. Another site of enrichment involves the concentration of uranium by organic or organically derived material. This accounts for the association of uranium with humates, coal (particularly lignites), oil, and peat.

IGNEOUS ROCKS

While uranium and thorium are observed in all major rock forming minerals (Table 1), the mechanics of location within the mineral are largely unknown. Generally, the mafic minerals, i.e., those enriched in magnesium and iron, are also enriched in uranium and thorium; but there are many exceptions. Accessory minerals, i.e., minerals occurring in small quantities in a rock, are usually greatly enriched in uranium and thorium, particularly in granites. Accessory minerals particularly enriched in thorium are allanite and monazite. Xenotime is enriched in uranium. The common accessory minerals, zircon and sphene, generally have a low Th/U ratio of 1 to 2 which may be either an expression of early magmatic composition or differential enrichment of uranium (Rogers and Adams, 1969a). The St. Francois Mountains of Missouri are noted as being enriched in uranium (10 to 30 ppm) and investigation of its petrography by Nash (1977, p. 30) revealed that 80 percent of the uranium is located as rims about magnetite crystals. Lesser amounts are associated with the biotite. Stuckless et al., (1977) noted similar patterns in magnetite

crystals at Granite Mountain, Wyoming. The biotitic phase is particularly enriched in uranium. They calculate an average uranium concentration of 9.8 ppm but if suggested levels of uranium loss are correct, the rock may have contained an average of as much as 30 ppm uranium. The content is highest in the accessory minerals zircon, sphene, and monazite with lesser amounts in epidotes, apatites and biotitic/chloritic alteration products (Stuckless et al., 1977). They also noted that uranium was not obvious in either intergranular borders or in fractures.

Before making generalizations on igneous rocks, it should be noted that some geographic areas have an overall elevated concentration of uranium and thorium regardless of rock type or geological age. Such areas include the Rocky Mountain Front (Phair and Gottfried, 1964) in Colorado and part of New England (Rogers and Adams, 1969a). Portions of central Wyoming as well as parts of the Colorado Plateau may also fall into this category (Stuckless, written communication, 1978). Putting such geographic variability aside, uranium content increases as the silica content increases. This property is the result of uranium exclusion from early minerals and rocks formed in the processes of magmatic differentiation. Whether intrusive or extrusive, igneous rocks tend to show similarity in uranium and silica distribution. While individual rock suites commonly exhibit uranium enrichment in later members, it is not universal (Rogers and Adams, 1969a). Thorium generally exhibits the same geochemical trends in petrological evolution as uranium (Rogers and Adams, 1969b). Thorium is also closely tied to potassium with a K/Th ratio "nearly constant...in a large variety of igneous rocks" (Heier and Rogers, 1963).

RESIDUAL IGNEOUS ROCKS

Pegmatites, possibly the last residual portion of a magma to crystallize, often move some distance from the parent magma. Enriched in a wide range of elements not easily incorporated into common minerals of the cooling magma, pegmatites have been used as a source of many rare metals including lithium, beryllium, scandium, rubidium, yttrium, zirconium, molybdenum, tin, cesium; the rare-earth elements, columbium (niobium), tantalum, tungsten, thorium, and uranium. Industrial minerals produced from pegmatites include feldspar, muscovite, phlogopite, tourmaline, and quartz (Mason, 1966; Bates, 1960).

Pegmatites are a complex group of rocks containing diverse mineralogical and compositional members. The largest pegmatite mines and the only ones which have operated on a more or less continuous basis are those extracting feldspar (Bates, 1960). Mica, spodumene, and beryl are often important by-products. Production is greatest in North Carolina with substantial production also in California, South Dakota, and Colorado. Usually, domestic pegmatites are not considered a commercial source of uranium and thorium. However, pegmatites having significant amounts of uranium stimulated some interest in the past (Lang, 1952; Page, 1950) and Charbonneau and Jonasson (1975) more recently referred to "radioactive pegmatites" in Ontario.
Garside (1973) indicates that uranium, thorium, and rare-earth minerals are common accessory minerals in pegmatites. He noted 33 so-called radioactive pegmatites occur in Nevada. Similar occurrences of radioactive minerals were observed in pegmatites around Kingman, Arizona (Peirce et al., 1970).

Uranium content appears to be strongly related to potash feldspar content of the pegmatites (Page, 1950). This appears to be a logical continuation of the geochemical behavior of uranium and potassium as observed in common igneous rocks. Radioactivity in pegmatites can have a broad regional impact. Dall'Aglio (1971) examined the uranium content of water in the Italian Alpine range and found anomalous areas. Subsequent radiometric surveys revealed that the source was pegmatites which contain 3 to 10 times the background uranium content.

Carbonatites are particularly enriched in a wide range of elements including rare-earth elements (lanthanides and yttrium). Deposits at Mountain Pass, California, constitute a major reserve of these materials. This deposit also contains the thorium minerals thorite and bastnaesite and less frequently monazite and allanite (Staatz, 1974). The vein was initially investigated as a result of elevated radioactivity. Nininger (1955) noted that thorium is found in a number of rare-earth minerals and identified Mountain Pass among 13 important thorium-bearing vein deposits in the United States. Association of rare-earth elements, uranium, and thorium has been observed in vein deposits in the Bokan Mountains of Alaska. Geological investigations by M. H. Staatz (1977) revealed that some of these veins are traceable for about 2.8 km and that uranium content varies from 0.005 to 2.8 percent while rare-earth elements and thorium concentrations vary between a few hundredths of a percent to over 10 percent. Enrichment of barium, beryllum, niobium, strontium, and zirconium has also been noted in these deposits. Because of the common associations of rare-earths and thorium, extraction of one could involve the extraction of the other as a byproduct or possible enrichment in the processing of wastes.

While of minor importance, another radiation source may be from several rare-earth elements which have radioisotopes including lanthanum-138, neodymium-144, samarium-147, and lutetium-176 (Lowder and Solon, 1956).

In summary, residual rocks like pegmatites may be enriched in uranium and thorium, particularly if the potassium content is high. Carbonatites with substantial rare-earth content appear to be somewhat radioactive.

URANIUM MINERALS IN METALLIC ORE DEPOSITS

Two approaches can be taken in analyzing uranium distribution in mineral deposits. One is to observe associations in uranium ore deposits. This can help to define geochemical affinities which may be applicable to other types of commodities and ore deposits. The second is to observe uranium minerals which occur in other types of ore deposits and thereby define potential radioactive hazards in other mineral extraction operations.

Many major metallic deposits are believed to have been generated by gases and liquids moving away from cooling magmas. Deposition of minerals from these fluids involves complex processes with definite geochemical associations among resulting mineral and element assemblages. In examining uranium ore deposits, several classifications have been developed based upon persistent mineralogical and chemical associations. McKelvey (1955) classified uranium vein deposits into three principal mineral groups: (1) nickel-cobalt-native silver-pitchblende, (2) pyrite-galena-pitchblende, and (3) uraniferous fluorite veins. Everhart (1956) also identified three types of deposits: (1) siliceous-pyrite-galena (a type of major importance), (2) nickel-cobalt-native silver, and (3) gold bearing pyrite. Everhart and Wright (1953) noted that epigenetic uranium deposits are more likely in veins containing either a) cobalt, nickel, and silver or b) copper, lead, zinc, and silver.

Direct mineral associations with uranium deposits may occur within the ore body or on a regional basis. In the Coeur d'Alene mining district, uranium

deposits are spatially associated with silver and base metal ores but exact genetic association is uncertain (Butler and Schnabel, 1956). Uranium deposits occur as part of the metal assemblage of ore deposits in the central mineral belt of Colorado (King et al., 1953), whereas those in the Front Range of Colorado are usually associated with molybdenum. Within this province, molybdenum is used as a geochemical indicator of possible uranium deposits (Ferris and Bennett, 1977). A similar relationship has been observed in the Marysvale, Utah, district (McKelvey et al., 1955).

McKelvey et al. (1955) noted that the list of metallic minerals found with uranium vein deposits is extensive. In their judgment, iron minerals are the most "nearly universal and conspicuous" association. The iron mineral may be pyrite or marcasite but finely dispersed hematite is considered to be potentially indicative of uraninite association. Magnetite is found associated with pitchblende at Maryvale, Utah, whereas some magnetite deposits in New Jersey and New York have trace amounts of uraninite. In general, "...large magnetite iron ore bodies of the world are not abnormally radioactive" (McKelvey et al., 1955).

The second most common metallic element associated with uranium deposits is copper. Most common copper minerals have been observed with uraninite ore types. Uranium minerals are also commonly associated with those containing cobalt which is an important geochemical indicator, particularly for the Ni-Co-Ag uranium ore type (McKelvey et al., 1955).

Lead is the next metal in abundance in uranium deposits. Galena is the principle mineral observed, but "...lead-bearing veins are singularly

nonradioactive" (McKelvey et al., 1955). After lead in abundance is nickel which, when associated with uranium, is generally restricted to cobalt-nickel-silver ore types. Nickel deposits not characterized by the cobalt-silver association are not usually observed to be particularly radioactive.

Minerals containing silver tend to coexist with uraniferous veins but are zoned in such a fashion that the association is more regional than local. Although zinc is also found in uraniferous veins, "...many rich zinc ores throughout the world are nonradioactive" (McKelvey et al., 1955).

Other metallics of note are molybdenum, native bismuth, titanium, and vanadium. Molybdenum minerals are observed in the Marysvale district, Utah and in other mining districts. Occurrence is more likely in the Si-Fe-Pb ore type. Native bismuth is generally restricted to the Co-Ni-Ag ore type. Bismuth ores tend to be slightly radioactive. Titanium occurrence is localized and tends to occur together with uranium in the same mineral, davidite. Vanadium is sporadically present and most common in low temperature uranium deposits. Carnotite, a potassium-uranium vanadate, is the most common mineral (McKelvey et al., 1955).

Uranium minerals have been observed in a variety of hydrothermal metallic ore deposits. Butler and Schnabel (1955) indicated that uranium was found associated with base metal sulfides and precious metals in several western states and Michigan. Usually reserves of uranium are low, typically less than 1000 tons of uranium ore (of unspecified grade). Traces of uranium have been found with gold and zinc minerals (Leonard, 1952). Investigation of mercury

deposits in the McDermitt caldera in Nevada-Oregon by Rytuba (1977) revealed that associated opalitic material contained up to 520 ppm uranium.

Uranium is also observed in iron formations. Everhart (1956) noted that uraninite is associated with various iron minerals in the iron-bearing strata and quartzite of upper Huronian age metasediments in Michigan. Uranium in iron formations is often associated with copper, lead, and zinc (Butler and Schnabel, 1956). While uranium may occur with iron minerals, thorium has been observed as detrital grains of monazite in the associated metasediments as observed in rock dumps of abandoned iron mines in Marquette County, Michigan (Vickers, 1956). The Old Bed Mine, a magnetite deposit near Mineville, New York, has thin seams of fluorapatite "usually rich in thorium and rare-earths." Similar type deposits exist elsewhere in the area (Twenhofel and Buck, 1956).

Uranium minerals in the Camp Smith area of New York occur in a complex sequence of Precambrian metamorphic rocks. Uraninite occurs in association with several lithologies as well as with a massive strata-bound Cu-Ni ore body (Grauch and Campbell, 1977). Popenoe (1966) noted that a major aero-radioactivity anomaly was associated with a mine positioned on the sulfide ore body.

The strongest association of uranium with gold tends to occur in metasediments, particularly conglomerates. Vein deposit associations are infrequent but have been observed in the Front Range of Colorado. Metasediment deposits include the Missisagi Conglomerate of the Blind River District, Ontario and the Witwatersrand Conglomerates in South Africa.

The occurrence of uraninite in the Witwatersrand gold deposits of Precambrian age was first noted by Cooper (1923). Subsequently it was determined that a frequently observed ore component referred to as "carbon" was an uraninite-carbon aggregate (Davidson and Bowie, 1951). The average ore grade in terms of uranium is approximately 0.03 percent. Generally, mine operators considered gold to be enriched when "carbon" occurred in greater amounts (Park and MacDiarmid, 1970). Substantial uranium has been recovered as part of gold processing in South Africa beginning near the conclusion of World War II. Uranium, in fact, has become more important than gold production in some parts of the Witwatersrand district (Nuclear Fuel, 1977b). In some cases, defunct gold mines are being re-evaluated in terms of potential uranium production (Nuclear Fuel, 1977a).

Uranium minerals have been observed in a variety of fluorite deposits. Brown et al. (1954) noted that uranium minerals occur in fluorite deposits in Illinois, and Wilmart et al. (1952) observed that in the Rocky Mountain area uranium can either be disseminated as discrete mineral grains or contained within the host mineral of the fluorite ore bodies. Secondary uranium mineral coating in fractures and vugs in both fluorite ore bodies and adjacent wall rock was also recorded. Butler and Schnabel (1956) noted that 20 fluorite deposits or "fluorite-bearing ores" had noticeable uranium.

From a broader geochemical viewpoint, Van Alstine and Shawe (1976) observed that fluorine has a tendency to be associated with beryllium, manganese, columbium (niobium), tin, tungsten, uranium, yttrium, lead, and zinc. McKelvey et al. (1955) noted that fluorite is a persistent, but minor, constituent of a majority of uranium vein deposits. While uranium is

associated with fluorspar deposits in the western United States, deposits in the central and eastern United States, outside of the Illinois-Kentucky district, exhibit thorium minerals as a possible associated constituent (Heyl and Van Alstine, 1976). It would appear that fluorspar may exhibit radioactivity either from the uranium series or thorium series. Griffitts and Van Alstine (1976) suggest that radioactivity may be a useful tool for exploration of fluorspar-uranium deposits similar to those seen in the Thomas Range, Utah, which contains "the largest known uraniferous fluorspar deposit in the United States" (Staatz and Osterwald, 1956). The extreme case of uranium mineral association with fluorite is the Marysvale, Utah ore body which is an important source of uranium. Currently, exploration for uranium has been planned for fluorspar claims in Utah (Engineering Mining Journal, 1978; p. 149).

SUMMARY

In summary, uranium ore deposits are associated with a wide variety of metallic and nonmetallic elements. In vein deposits, McKelvey (1955) ranked the following metallic elements found with uranium vein deposits (in descending order of uranium abundance): iron, copper, cobalt, lead, nickel, silver, zinc. Gold is occasionally noted. Important nonmetallic elements include silica and fluorine. Precambrian iron and magnetite deposits on the U.S. east coast contain uranium minerals. Gold and uranium are observed in metasediments. Fluorite deposits can contain either uranium or thorium minerals.

WEATHERING AND SEDIMENTARY CYCLE

INTRODUCTION

It is during weathering and the sedimentary cycle that major separation occurs between uranium and thorium. This is due in part because uranium oxidizes to a relatively soluble uranyl ion compared to the thorium form. Uranium deposition is occasionally difficult to explain due in part to the obvious absence of reducing agents of any sort to act on the uranyl ion. Krauskopf (1976) suggests that under conditions of alkalinity and carbonate ion availability, highly soluble uranium carbonate complexes may form and contribute to uranium mobility. Experimentation conducted by Naumov and Mironova (1969) substantiate this suggestion as well as showing that carbonate complexes may also play a role in uranium mobility even with temperatures in the range of 100 to 200°C. Uranium deposits appear to be related to reduction in carbonate content by either carbon dioxide degassing or wall rock interaction.

When rocks are subject to weathering, thorium either remains tied up in resistate minerals or is "...strongly adsorbed by clay particles or present as insoluble oxides and hydroxides" (Ames and Rai, 1978). Thorium resistance to chemical mobility is well exhibited in extremely weathered soils. Bauxites, which are one end product of intense weathering, may have thorium concentrations up to 50 ppm or more (Adams and Richardson, 1960). In summary, uranium is moved into the environment of sedimentary deposition in solution;

thorium is moved into the depositional environment associated with discrete grains. This fundamental behavioral difference effectively decouples the two elements (Table 3).

RESISTATE DEPOSITS

In igneous rocks, trace minerals bearing significant amounts of thorium are usually resistant to surface and near surface chemical weathering processes. Such minerals will largely be mobilized only when the grains are physically transported in a high energy environment typified by fluvial and/or beach settings. Due to their higher specific gravity than the associated quartz and clay particles, these mineral grains may become concentrated. Such deposits have been subject to extensive study, particularly in Brazil (Roser et al., 1964; Penna-Franca, 1975). Some of these beach deposits are utilized as a source of thorium. Other mineral resources (e.g. rutile) concentrated by similar processes may also contain substantial concentrations of radioactive resistates.

Placer deposits generated by streams and rivers as well as by shoreline processes could contain a variety of deposits of economic importance including gold, platinum, and inert oxides and silicates of zirconium, tin, chrome, tungsten, and titanium (Park and MacDiarmid, 1970). The radiation hazard, if any, from such deposits is dependent on the geology of the source area, positioning of the deposit relative to the land surface, and a host of variables relating to land and water use by man or segments of the human food chain.

Because of elevated radioactivity, placer deposits along streams in Idaho have been investigated. Mackin and Schmidt (1956) concluded that most of the radioactive minerals found in the placer was derived from quartz monzonite, a component of the Idaho batholith. The placers in Bear Valley are particularly enriched with these minerals. In some areas, monazite, and euxenite occur in the ratio (by weight) of about 1:2 with approximately 0.5 pounds monazite per cubic yard (Mackin and Schmidt, 1956). During the interval of 1955 to 1960 a plant 20 miles to the south at Lowman, Idaho processed about 200,000 tons of placer material from Bear Valley. Minerals extracted include columbite, euxenite, monazite, magnetite, ilmenite, zircon, and garnet. Subsequent inspection of the plant site was made to assess potential radiation hazard (Ford, Bacon, and Davis, Inc., 1977). While thorium is an obvious portion of the ore mineralogy, no attempt was made to quantify the potential radiation hazard from the thorium-232 decay scheme. The uranium-238 decay chain was addressed, however.

Placers of various ages may contain thorium. Twenhofel and Buck (1956) observed Precambrian age quartzites which contain thorium minerals. Previous discussion touched on the fact that detrital grains of monazite in metasediment of possible placer origin are adjacent stratigraphically to Precambrian age iron formation. The Witwatersrand gold deposit is accepted by some as a placer deposit. Overall, gold placer deposits have been the subject of extensive exploitation. There also has been substantial interest in titanium deposits in eastern Florida beach deposits (Lynd, 1960; Park and MacDiarmid, 1970). The two principal deposits are located at Trail Ridge and east of Jacksonville with monazite being identified among the mineral assemblage of the former. Numerous occurrences of titaniferous sands are common in Florida

but are usually less than commercial grade. Sand sampled from Venice Beach was found to contain between 0.05 and 1.5 percent monazite (Florida Department of Health and Rehabilitative Services, 1976). In general, Florida "black" sand contains 250 to 1000 ppm thorium with an average of 300 ppm and about an order of magnitude less uranium (Osmond, 1964).

Processing of heavy sands has created some radioactivity problems. In Albany, Oregon there has been extensive processing of zirconium as well as other rare metals including columbium, tantalum, and hafnium (Boly, 1977). Ore of these metals usually contains substantial radioactivity, which in the Wah Chang operation is concentrated in a "flour-like mineral residual" which is radioactive. Leachate water associated with wastes buried on the plant site contained on the order of 45,000 pCi/l of radium-226 (State of Oregon Health Division as cited in Boly, 1977). Approximately 4000 tons of this waste material are located at the plant site with similar material disposed of at several locations outside the plant site, including the Coffin Butte landfill near Adair Village.

In summary, placer deposits of any type have a potential for elevated radioactivity during mineral extraction and processing. The thorium-232 decay series is especially, but not exclusively, the source of activity.

RESIDUAL DEPOSITS

While soil can be expected to reflect some properties inherited from the underlying bedrock, significant deviations are observed in radioactivity levels between the two. Soils are the result of complex chemical, biological, and physical processes which alter the concentration of certain elements. This is particularly true when conditions involve extensive, long-term chemical weathering and minimal physical transport. For example, Pinkerton et al. (1964) found that the soil over limestone in Maryland was quite radioactive despite the low activity of limestone. This is due in part to selected concentrations of radioactive elements in the parent rock as it weathers into soil. Bauxites, the principal aluminum ore, are complex aggregates of iron and aluminum minerals which form as residual deposits, often over limestone, under tropical climatic conditions (Park and MacDiarmid, 1970). They have been observed to have substantially higher levels of uranium and thorium (Polanski, 1965) than the parent limestone (Table 3). Although not significant in the continental United States, important residual ores include manganese oxides in India and nickel in New Caledonia (Park and MacDiarmid, 1970).

ORGANIC MATTER ASSOCIATIONS

While it is beyond the scope of this report to detail the relationships, organic matter can play an important role in uranium deposition. Much of the radioactivity in sedimentary rocks is found to be related to organic residues. Breger and Deul (1956) note that the close association between carbonaceous

material and uranium may be the result of three mechanisms: (1) organic matter acts directly as a reducing agent converting the soluble uranyl complex to insoluble uranous ion, (2) sulfide ubiquitously present in organic debris acts as the reducing agent and, (3) the carbonaceous material acts as a chemical precipitant in some unknown fashion. Jennings and Leventhal (1977) proposed a structural model of humic-acid type material which identifies sites for uranium attachment.

Organic materials which can exhibit substantial uranium enrichment include coal (esp. lignite), humate, black shale, asphalt, and oil. Armstrong and Heemstra (1973) noted that as oil becomes more oxidized or asphaltic, total uranium content increases. Rocks with unusually high levels of organic residue or asphalt-bearing rocks also tend to exhibit higher levels of radioactivity. Hail et al., (1956) found that ash of the extracted oil contained from 0.028 to 0.376 percent uranium. Uranium is clearly confined to the organic fraction of material and not in the confining rock. Uranium is enriched in lignite, particularly in deposits in the upper Great Plains (Vine, 1956). Denson et al. (1960) analysed 275 surface and 1000 core samples and found uranium content to vary between 0.005 and 0.02 percent.

Living organic matter may even have a more active role in uranium deposition. Jensen (1958) suggests that anaerobic bacteria may act as a source of hydrogen sulfide which in turn promotes uranium precipitation.

In summary, organic matter is an important agent which can concentrate uranium in the sedimentary cycle. In contrast, thorium is enhanced in residual or resistate deposits such as placers and soil.

MINERAL EXTRACTION AND RADIOACTIVE BYPRODUCTS

A specific mining operation may involve elevated (relative to background) radioactivity if the principal ore material contains or is associated with uranium and/or thorium and their daughters. Obviously, the potential for a radiological health hazard depends on whether significant amounts of radionuclides are present and benefaction results in sufficient radioactivity to be of concern in the product, waste, or environs. Radioactivity levels so created may increase occupational and/or general population exposure. The occurrence of radioactivity in byproducts is also cause for concern. In certain instances, uranium is, or soon will be, recovered as a byproduct of phosphate, copper, and gold extraction. For example, the Central Florida Land-Pebble Phosphate District was initially identified as having significant amounts of uranium (Cathcart, 1963a; 1963b; 1963c; 1964; 1966) yet large scale byproduct extraction during phosphate processing only began in late 1975 (Finch, 1977). The potential radiological hazard posed by phosphate mining and processing has only recently been evaluated, partly in response to increased local population and competition for land and water.

Byproduct production of uranium is being implemented as part of copper extraction in Utah. Another operation proposed in Utah involves extraction of uranium from beryllium ore (Engineering and Mining Journal, 1978; p. 149). In the Witwatersrand district of South Africa, uranium minerals were reported as part of the ore mineralogy as early as 1923 (Cooper, 1923). However, by-product recovery of uranium was not attempted until the latter part of World

War II. In some cases uranium has become the principal metal of economic interest. As the demand for uranium increases, other mining industries are likely to become potential sources of uranium or thorium. As these new resource materials are identified, a need will develop to identify potential radioactivity problems they may pose.

In summary, uranium byproduct extraction has been made in phosphate, copper, and gold ore processing. Similar extraction operations have been suggested for beryllium ore in Utah.

RADIOACTIVITY MEASUREMENTS ASSOCIATED WITH MINING OPERATIONS

A limited amount of information concerning radiation and ratiation dose is available in and adjacent to non-uranium mining operations. Included in this category is information defining trace concentrations of uranium and thorium in ore bodies and surrounding terrain. The Mine Safety and Health Administration (MSHA) is the principal Federal Agency concerned with radiation levels in underground mine air and the principal source of the information presented herein (Rock, 1977, written communications; Goodwin, 1978, written communications). Radioactivity measurements made to date in mines are primarily concerned with the assessment of potential hazard to miners and may not or may only indirectly relate to ore geochemistry. Radon in some mines has been attributed to sources other than the ore, as in the case at the Pine Creek tungsten mine, California where ground water is believed to be the radon source (Rock, 1977, written communication). Secondly, the presence or absence of ventilation may play an important role in mine air radioactivity. Clearly, an underground operation which for a variety of reasons has excellent ventilation can have low concentrations of airborne radioactivity but a high overall radioactivity potential. Procedural variability in atmospheric radiation measurements made by MSHA is also present (Andrews, personal communication, 1978). In general the available data are very limited and vary from qualitative to quantitative. It includes observations from both water and air measurements. It is unknown how representative these numbers are. It is also unknown how the available observations on activity levels relate to water and air outside the mine or how they interrelate to other possible

radiological source terms of the mining operation. Radium-226 levels in mine related water are expressed as picocuries per liter (pCi/l). For the purposes of this report they are compared to the 5 pCi/l limit of radium-226 plus radium-228 set by the national interim primary water regulations (USEPA, 1976). Selected ores or mines will be noted if radon/radon daughters are thought to be elevated (subjective experience of Rock, personal communication, 1977) but exact values are not available. Otherwise, radon/radon daughters are expressed as working levels (WL). All the quantitative data from MSHA were taken from a list of observations of 0.1 WL or greater. Therefore, they may not be typical of the vast majority of operations in a given mineral industry. (A WL is defined as any combination of short lived radon daughters in 1 liter of air which will produce 1.3×10^5 million electron volts of potential alpha energy.) MSHA regulations require corrective action when mine atmosphere levels exceed 1.0 WL.

Substantial effort has been made to investigate radioactivity associated with ore bodies. In part, this is to determine whether radioactivity may be helpful in exploration and ore definition. Gross (1952) inspected gold mines located in igneous stocks in Canada and found that elevated radioactivity was a pervasive feature. Moxham et al. (1965) observed that uranium was enriched about four times that of the surrounding country rock in the Bagdad Copper Mine, Arizona. However Moxham et al. (1965) also conducted radiation surveys of three Precambrian age massive sulfide deposits in North-Central Arizona: 1) United Verde/United Verde Extension Mine at Jerome, a massive copper-zinc deposit; 2) Iron King Mine, a massive lead-zinc deposit; 3) Old Dick Mine near Bagdad, a massive copper-zinc mine. No significant systematic dependency was observed between uranium or thorium content in either the alteration or

mineralized configuration of any of the mines. Gangadharam et al. (1963) similarly noted that the copper and uranium content were essentially independent in the environment of a massive sulfide ore body at the Mosaboni Copper Mine, India.

Fitzgerald (1976) reviewed the literature concerning radioactivity associated with low grade copper deposits. One of the principal contributors he notes is Still (1962) who observed the uranium content of various porphyry copper deposits in the Miami District of Arizona. The geometric mean of 140 observations by Still (as given by Fitzgerald, 1976) at the Copper City Mine is about 50 ppm uranium. A second mine in the district, the Castle Dome, had a geometric mean of approximately 10 ppm. Apparently within the same mining district, the uranium content of similar ore body types may vary considerably. The enrichment of potassium is a common feature of porphyry copper deposits and attributed to a variety of processes (Davis and Guilbert, 1973). Potassium-40 is a radioisotope which makes up about 0.01 percent of natural potassium and may contribute to the overall radioactivity of an ore body (Davis and Guilbert, 1973). They note that others in the area of theoretical crystal chemistry have suggested that uranium as well as thorium could also be enriched along with potassium. However, investigation by Davis and Guilbert (1973) of four porphyry copper mines and adjacent geologically similar features without copper mineralization revealed that uranium and thorium are not systematically enriched as a result of or in association with copper mineralization. A weighted average uranium content from mineralized occurrences is 0.95 ppm (Data taken from Table 1; Davis and Guilbert, 1973; p. 157). For barren sites the weighted average uranium content is 0.63 ppm.

Analysis by the U.S. Bureau of Mines of 4 copper, 1 molybdenum, and 5 lead-zinc tailing samples revealed less than 30 ppm U_3O_8. One lead-zinc tailing sample contained 60 ppm U_3O_8 and a phosphate tailing sample contained 150 ppm U_3O_8 (written communication, K. Dean, U.S. Bureau of Mines to R. Snelling, 1970). Addressing the problem from a mineralogical point of view, trace amounts of uranium in pyrite, sphalerite, and galena have been observed to vary from one to several thousand parts per million (Wright et al., 1960). They suggest that in samples with greater than 80 ppm, uranium appears to be irregularly distributed and, therefore, not strongly related to the fluid which deposited the metal sulfide. Stuckless (written communication, 1978) suggests that this may even be true for concentrations even greater than 8 ppm. Apparently trace amounts of uranium in sulfides are related to secondary processes or microcrystalline minerals not directly tied to sulfide deposition. Secondly, uranium content appears to be dependent more on regional availability than on mineral genesis.

Metallic commodities and associated radioactivity observations are summarized in Table 4. Radium-226 data are taken from Supplement B-13, radiological data, Calspan Corp. (1975) and air sampling data supplied by MSHA. Working levels shown are derived from a list which notes underground mines with at least one sample of 0.1 WL or greater. For commodities with three or more maximum WL observations available, the rank from highest to lowest is 1) molybdenum, 2) iron, 3) lead/zinc, and 4) gold. If all commodities are pooled, the average maximum WL is 0.54. Only molybdenum is greater (0.83) in terms of average maximum WL and iron has approximately the same value as the pooled average. For commodities with only one or two observations the highest was antimony followed by copper, tungsten, and

silver. The single available maximum WL observation for antimony is 0.91; the average for two copper values is 0.70; the average for two tungsten values is 0.61 and for silver is 0.24. When analyzed in terms of WL and rejecting single values, the commodities with possibly the greatest air concentration of radon-222 progeny are: 1) molybdenum, 2) copper, 3) tungsten, and 4) iron.

The radium-226 data base from water samples is extremely incomplete. For all commodities pooled, the average radium content is 17.3 pCi/l. If the extremely high value in a gold mine is excluded (81.7 pCi/l), the average radium content is 9.2 pCi/l. Data values appear to be extremely high or low (see Appendix A). If observed radium-226 activity in water from various parts of the metallic mineral extraction industry are indicative, radium-226 content of water sampled is elevated and in general would exceed the 5 pCi/l standard. Such a direct comparison is probably not strictly valid particularly considering that the waters tested are not intended for potable use. Nevertheless there is some possibility that a radiological health hazard may exist in process water associated with metallic mineral extraction operations. Radium-226 data ranked in decreasing concentration for these commodities with observations greater than 9.2 pCi/l are: 1) gold, 2) iron, 3) molybdenum, and 4) aluminum.

Among the nonmetallic commodities, fluorspar appears to have significantly greater concentrations (1.2 WL) in mine atmospheres (Table 5), although these are associated with low ventilation rates. The Federal Radiation Council (1967) reported that radon in a fluorspar mine in Newfoundland in areas of restricted ventilation exceeded 1000 pCi/l. Also, tailings from a fluorspar operation near Golden, Colorado have gamma radiation levels on the order of

1 mR/h (USEPA, 1976). The pooled average maximum WL for nonmetallics was 0.56 which is very close to 0.54 observed for the metallics. The highest number reported was 1.6 WL for a phosphate mine, but since phosphates are excluded from this discussion, this value will not be used. Outside of these two observations maximum working levels are much lower, possibly indicating that fewer nonmetallic mine and milling operations bear much additional study. Robbins (written communications, 1977) noted that MSHA also reported significant amounts of radon-222 in fluorspar related mines with about 500 pCi/l reported. Similarly, about 100 pCi/l radon-222 was noted in underground granite, marble, and limestone operations.

SUMMARY

CONCLUSIONS

1. The overall geochemical properties of uranium and thorium suggest that cerium, zirconium, and the rare earth elements should be associated.

2. Uranium and thorium content of igneous rocks generally increases with increasing silica and with increasing potassium. Some mafic and accessory minerals are much more enriched than the felsic minerals. Thorium content of igneous rocks closely follows the potassium content.

3. Certain areas such as the Front Range in Colorado and portions of New England are broad regions of overall enrichment in uranium and thorium.

4. Pegmatites may be enriched in uranium, particularly if the potassium content is elevated.

5. Carbonatites can be enriched in uranium and thorium, particularly if rare-earth content is high.

6. Some rare-earth elements have radioisotopes which may contribute to overall radioactivity of an REE ore body.

7. Hydrothermal mineral deposits exhibit a broad spectrum of geochemical and mineralogical association with thorium and uranium. The three principal metals observed in vein type uranium deposits are iron, copper, and lead. Uranium minerals have been found in many different types of deposits including ores for gold, silver, and iron.

8. The distribution of trace amounts of uranium is homogeneous in pyrite, sphalerite, and galena at concentrations less than 8 ppm uranium. Trace amounts of uranium greater than this are irregularly distributed and presumably not strongly related to the deposition of the host minerals.

9. Fluorspar deposits appear to be more radioactive than most other non-metallic ores. Both thorium and uranium minerals have been observed with fluorite.

Fluorspar deposits have been noted as having significant radioactivity in associated underground mine atmosphere and mine tailings. Radioactivity of fluorspar deposits has been suggested as a useful exploration tool.

10. Uranium is generally soluble and mobile in the sedimentary cycle. Uranium may be stabilized by organic matter. Thorium minerals are resistant to surface weathering and tend to be concentrated in placers or in residual soil (such as bauxite).

11. Byproduct recovery of uranium from phosphate, copper, and gold ore processing is underway and is proposed for beryllium ore.

12. With the exception of uranium and phosphate ore bodies and to a lesser extent in the case of placer deposits of resistate minerals, no persistent pattern of radioactivity is associated with ore bodies. Radioactivity may vary substantially between ore bodies with similar mineralogy and genesis. Mines of gold, copper, and iron have been observed with elevated radioactivity.

13. Observations on radioactivity of mine atmospheres are of questionable validity. Preliminary information suggests that higher working levels are associated with molybdenum, copper, tungsten, and iron.

14. Radium-226 observed in various types of mine related water tends to be elevated. The highest concentrations observed, in descending order, are gold, iron, molybdenum, and aluminum.

RECOMMENDATIONS

1. Radiological surveys of various mining industries need to be made for both the uranium and thorium decay series. Rare-earth element radioisotopes and potassium-40 may be important in certain situations.

2. Atmospheric radioactivity levels in underground mines may be poorly related to ore geochemistry. Radon levels have been found to be substantial in limestone caves despite the fact that limestone has low concentrations of both uranium and thorium (see Table 3). Detailed information is required on ventilation before valid conclusions can be attempted.

3. Mineral extraction appears to enhance radium-226 concentrations in mine related water. Further investigation is appropriate in this area.

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APPENDIX A. RADIOLOGICAL DATA FOR SELECTED METALLIC COMMODITIES

Commodity	State - Mine	Water Type	Radium-226 pCi/l	Atmospheric Radioactivity* WL Observed
Aluminum	Arkansas			
	Bauxite	Mine	32.2 ± 2.3	-
		Wastewater	2.15 ± .22	-
		Basin c(?)	4.6 ± .62	-
Antimony	Montana			
	Babbitt	-	-	.47 (.91)
Copper	Arizona			
	Mammoth Mt.	300 Level, Mine	2.6 ± .26	-
	Bagdad	Pit Mine	1.6 ± .16	-
	Copper Queen	-	-	Yes**
(& Silver)	Red Rover	-	-	- (1.2)
	Michigan			
	White Pine	Discharge #1	27.3 ± 2.7	-
		Discharge #2	4.18 ± .46	-
		Discharge #3	13.6 ± 1.4	-
	Montana			
	Butte	Mine	4.79 ± .48	-
		Mine	1.52 ± .15	-
		Mine	2.95 ± .53	-
		Input to emergency pond	1.72 ± .17	-
	Tennessee			
	Boyd	-	-	.089(.207)
Gold	Colorado			
	Brooklyn	-	-	.15 (1.15)
	Nevada			
(& Silver)	Gooseberry	-	-	.17 (.2)
	Oregon			
	Buckeye	-	-	.13 (.13)
	Bald Mountain	-	-	.17 (.32)
	South Dakota			
	Homestake	Mine	81.7 ± 8.2	-

Footnotes - See end of Appendix

APPENDIX A. RADIOLOGICAL DATA FOR SELECTED METALLIC COMMODITIES (Continued)

Commodity	State - Mine	Water Type	Radium-226 pCi/l	Atmospheric Radioactivity* WL Observed
Iron	Michigan			
	Mather B	-	-	.21 (.49)
	Sherwood	-	-	.51 (.9)
	Missouri			
	Pilot Knob	-	-	- (.26)
	Pea Ridge	-	-	- (.642)
(Magnetite)	Pennsylvania			
	Grace	Mine	16.6 ± .7	.14 (.14)
Lead/Zinc	Colorado			
	Leadville Unit	-	-	.21 (.42)
	Idaho			
	Kellogg	Mine	3.01 ± .30	-
(Lead/Silver)	Muldoon Barium	-	-	- (.23)
	Silver Empire	-	-	.37 (.37)
	Horseshoe	-	-	(.18)
(Zinc Only)	Tamarack	-	-	.2 (.7)
(Zinc Only)	Star	-	-	.08 (.2)
(Zinc Only	Bunker Hill	-	-	.07 (.2)
	Missouri			
	Bixby	Mine/Mill (treated)	<1	-
(Lead Only)	Indian Creek	-	-	- (.17)
(Lead Only)	Viburnum #27	-	-	- (.11)
(Lead Only)	Viburnum #28	-	-	- (.15)
	New York			
	Balmat	Pond Effluent	<1	-
		Mine Drainage	27.8 ± 2.8	-
	Oklahoma			
	Eby	-	-	Yes**
	Pennsylvania			
	Central Valley	Mine	<1	-
	Utah			
(Lead & Silver)	Deertrail	-	-	- (.25)
	Washington			
	Pend Oreille	-	-	.70 (1.4)

Footnotes - See end of Appendix

APPENDIX A. RADIOLOGICAL DATA FOR SELECTED METALIC COMMODITIES (Continued)

Commodity	State - Mine	Water Type	Radium-226 pCi/l	Atmospheric Radioactivity WL Observed
Molybdenum	Colorado			
	Climax	Mine	15.8 ± 1.6	.24 (.38)
	Henderson	-	-	.21 (1.56)
	Idaho			
	Thompson Creek	-	-	- (.54)
Nickel	Oregon			
	Nickel Mountain	Slag	8.23 ± 83	-
Silver	Idaho			
	Sunshine	Mine	4.47 ± .45	-
	Silver Empire	-	-	.37 (.37)
	Crescent	-	-	.04 (.10)
Tungsten	California			
	Pine Creek	-	-	.31 (.72)
	Nevada			
	Emerson	-	-	.1 (.5)
Vanadium	Arkansas			
	Garland Operation	Mine	2.44 ± .5	-

* Underground operations, Average WL followed by maximum WL in brackets.

** Yes - R. Rock, MSHA, 1977, indicated that significant atmospheric radiation was observed but no quantitative measurements are available.

APPENDIX B. RADIOLOGICAL DATA FOR SELECTED NONMETALLIC COMMODITIES

Commodity	State - Mine	Water Type	Radium-226 pCi/l	Atmospheric Radioactivity* WL Observed
Clay	Pennsylvania			**
	Kitanning	-	-	Yes
	Continental Clay	-	-	.4 (.4)
	Ohio			
	Dando	-	-	.37 (.46)
	Irondale	-	-	.10 (.13)
	Strong Creek Brick	-	-	.18 (.24)
	West Virginia			
	Globe Clay	-	-	.3 (.3)
Fluorspar	Arizona			
	Western Fluorspar	-	-	.9 (2.2)
	Colorado			
	Burlington	-	-	Yes
	Nevada			
	Crowell Fluorspar	-	-	.9 (1.0)
	Texas			
	Paisano Underground	-	-	.3 (.41)
Gypsum	Virginia			
	No. 6 Mine	-	-	.28 (.30)
Limestone	Illinois			
	Alton	-	-	.05 (.16)
Phosphate	Montana			
	Brock-Warm Springs	-	-	.75 (1.6)
Silica Sand	Wisconsin			
	Bay City Sand	-	-	.13 (.19)
Talc	Vermont			
	Windham	-	-	.18 (-)

* Underground Operations, Average WL followed by maximum WL in brackets
** Yes - R. Rock, MSHA, 1977, indicated that significant atmospheric radiation was observed

APPENDIX C. GLOSSARY OF GEOLOGICAL TERMS USED

ALLANITE - A mineral of variable composition of the epidote group with general formula $(Ca, Ce, La)_2(Al, Fe, Mg)_3(SiO_4)_3$ (OH); may contain Th as much as 3.2 percent.

APATITE - A mineral group with the general formula $Ca_5(PO_4)_3$ (OH, F,Cl). Fluorapatite $[Ca_5(P_4O_4)_3F]$ is by far most common and apatite is used synonymously with fluorapatite.

BASE METAL - Metal of less value than gold or silver; generally considered to be one of the following: copper, lead, zinc, tin, or mercury.

BASTNAESITE - A complex fluorcarbonate of the rare-earth elements principally cerium and lanthanum and usually less than one percent uranium and thorium; occur in metamorphic contact zones.

BATHOLITH - A body of intrusive rock at least 40 square miles in surface exposure.

BAUXITE - A rock composed of aluminum hydroxides and impurities in the form of free silica, clay, silt and iron hydroxides; the principle ore of aluminum.

BERYL - A mineral with the formula $Be_3Al_2(Si_6O_{18})$ but may also contain Na, Li, Cs and occasionally Rb.

BIOTITIC - Containing biotite, an iron rich tri-octahedral mica.

CARBONATITE - An intrusive igneous rock of high carbonate content and usually enriched in a wide range of rare elements.

CENOZOIC ERA - The time interval covering the last 60 million years.

CHLORITIC - Containing chlorite, a mica-like mineral of the formula $(Mg, Al, Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$.

CLAY - Crystalline fragments of minerals that are essentially hydrous aluminum silicates or hydrous magnesium silicate.

COLUMBITE - A mineral, the Nb - rich end member of the columbite - tantalite series $(Fe,Mn)(Nb,Ta)_2O_6$.

CONGLOMERATE - A rock made up of pebbles and other rock fragments (usually rounded) cemented together.

DETRITAL - Consisting of mineral or rock fragments.

EPIGENETIC - Refers to a process in which minerals undergo changes as result of external processes usually at or near the earth's surface.

EPIDOTE - A mineral of the formula $Ca_2(Al, Fe^{+3})_3(SiO_4)_3(OH)$.

EUXENITE - A complex oxide mineral containing thorium, rare-earths, niobium, tantalum, calcium and titanium; occurs as an accessory mineral in granitic rocks.

FELDSPAR - A group of minerals commonly in most rocks with the general formula $XAl(Al,Si)_3O_8$ where X = K, Na, Ca as the major ions, and Ba, Rb, Sr as trace ions usually less than 1500 ppm.

FLUORAPATITE - A mineral of the apatite group with the formula $Ca_5(PO_4)_3F$.

FLUORITE - See Fluorspar below.

FLUORSPAR - A mineral, CaF_2, the principal ore of fluorine.

FLUVIAL - Of, or pertaining to, rivers; produced by river action.

FRACTIONATION - The process by which a mixture is broken down into components.

GALENA - A mineral with formula PbS.

GARNET - A mineral group, with a general formula $X_3Y_2(SiO_4)_3$ where X = Ca, Mg, Fe^{+2}, and Mn^{+2}; Y = Al, Fe^{+2}, ,Mn^{+2}, and Cr.

GRANITE - A silica rich igneous rock with minerals discernible to the naked eye consisting of alkali feldspar and quarts with minor muscovite, biotite, and hornblende.

HURONIAN - A subdivision of Precambrian rocks identified in the Canadian Shield which range from about 800 to 1200 million years in age.

IGNEOUS - Formed by solidification from a molten or partly molten state.

ILMENITE - A mineral with the formula $FeTiO_3$; accessory mineral in many igneous and metamorphic rocks.

LIGNITE - Brownish-black coal composed of a plant residue more altered than peat but less than bituminous coal; less than 8300 BTU.

LIMESTONE - Sedimentary rock consisting mainly of calcium carbonate ($CaCO_3$).

MAGNETITE - A magnetitic iron mineral, $Fe^{+2}Fe^{+3}O_4$, occurring as an accessory mineral in igneous rocks and as an iron ore.

MAGMATIC DIFFERENTIATION - Operation by which various types of igneous rocks are separated from a single molten mass.

MARBLE - A rock, metamorphosed limestone or dolostone with more or less course-grained crystalline structure.

MARCASITE - A mineral of the formula FeS_2; pyrite is a different crystal form of the same chemical composite.

MICA - A mineral group of phyllosilicates with sheet-like structures.

MINERAL - A naturally occurring chemical element or compound having a definite range in chemical composition and characteristic crystal structure.

MONAZITE - A mineral $(Ce,La)PO_4$ commonly containing thorium as well as rare earth elements.

MUSCOVITE - A mineral of the mica group (which are characterized by a sheet-like structure) of the general formula $KAl_2(AlSi_3)O_{10}(OH)_2$.

OPALITIC - A material consisting of opal, with amorphorus hydrated silica.

PHLOGOPITE - A mica mineral with the formula $K_2(Mg, Fe^{+2})_6$ $[Si_6Al_2O_{20}](OH,F)_4$.

PITCHBLENDE - Another term for uraninite when massive.

PRECAMBRIAN - All geologic time previous to about 600 million years ago.

PYRITE - A mineral of the formula FeS_2 the most abundant sulfide.

QUARTZ - A mineral, SiO_4.

QUARTZITE - A rock of quartz grains bonded by metamorphism.

QUARTZ MONZONITE - An igneous rock (with minerals identifiable with the naked eye) which contains plagioclase (Na/Ca feldspar), orthoclase (K feldspar), and quartz with biotite and/or hornblende and accessory apatite, zircon and opaque oxides.

RESISTATE MINERALS - Those undecomposed residues of weathering.

ROCK - Any natural aggregate of mineral matter (or single mineral) constituting an essential part of the earth's crust.

RUTILE - A mineral, TiO_2.

SPECIFIC GRAVITY - Ratio of the mass of a body to the mass of an equal volume of water at a specified temperature.

SPHENE - A mineral with the formula $CaTiSiO_5$.

SPODUMENE - A mineral with the formula $LiAlSi_2O_6$.

THORITE - A mineral with the formula $ThSiO_4$.

TOURMALINE - A mineral, a complex borosilicate containing varying amounts of Na, Mg, Fe, Mn, Li, and Al.

URANINITE - A mineral, primarily UO_2 but also may contain Th, rare-earths, Ra, and Pb.

VEIN DEPOSIT - A mineralized zone long in two dimensions and thin in the third.

WEATHERING - Chemical and physical processes operating at the earth's surface on rocks resulting in change in character, decay, and finally crumbling into soil.

XENOTIME - A mineral YPO_4 also containing rare-earths, Th and U.

ZIRCON - A mineral, $ZrSiO_4$, a common accessory mineral, particularly in silica enriched plutonic rocks.

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TABLE 1. URANIUM AND THORIUM CONTENT OF MINERALS FOUND IN IGNEOUS ROCKS *

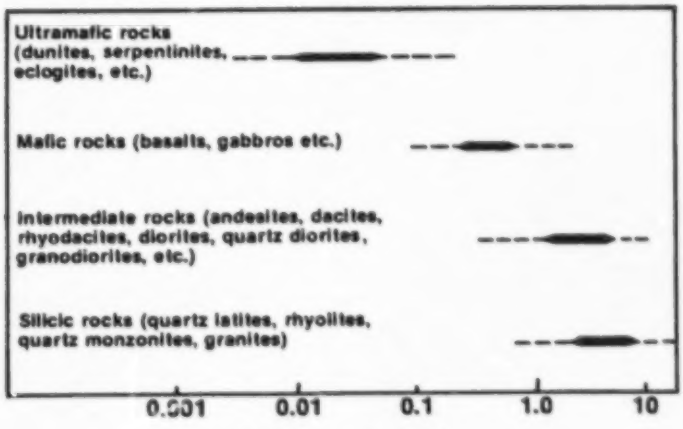
Major Mineral	Uranium ***	Uranium	Thorium
	Mean (ppm)	Normal Range (ppm)**	
Quartz	1.7	0.1-10	0.5-10
Feldspar	2.7	0.1-10	0.5-10
Biotite	8.1	1.0-60	0.5-50
Muscovite	- (?)	2-8	-
Hornblende	7.9 (?)	0.2-60	5-50
Pyroxene	3.6	0.1-50	-
Olivine	~ 0.05	-	~ 0.02
(mean)			

* Summarization of tables given in Rogers and Adams (1969a; 1969b)

** Normal range excluding extreme values

*** Recent work suggests that the quartz and feldspar values are too high, biotite is low by order of magnitude and pyroxene high by order of magnitude (Stuckless, 1978 written communication)

TABLE 2. GENERALIZED DISTRIBUTIONS OF URANIUM IN VARIOUS GROUPS OF IGNEOUS ROCKS



(Taken from Rogers and Adams, 1969b)

TABLE 3. URANIUM AND THORIUM CONTENT OF SELECTED SEDIMENTARY ROCKS*

Rocks	Thorium (ppm)	Uranium (ppm)
Sandstones		
Orthoquartzite (North American Avg.)	1.7	0.45
Graywacke (Est. Avg.)	2.8	2.1
Arkose	5	1.5
Shale		
Common Shale, Gray, Green, etc. (North American Avg.)	13.1	3.2
Black Shale	Low	8
Bauxites	48.9	11.4
Bentonites	24.0	5
Limestones (North American Avg.)	1.1	2.2
Dolomites (Range)	-	0.03-2.0
Phosphate Rock (Range)	1-5	50-300
Evaporites**	-	generally less than 0.1

* Summarization of tables given in Rogers and Adams (1969a, 1969b)

** Some evaporites can be important ore deposits particularly those found in Africa and Australia (Stuckless, 1978, written communication).

TABLE 4. SUMMARY OF RADIOLOGICAL INFORMATION ON METALLIC COMMODITIES GIVEN IN APPENDIX A

Commodity	Average Maximum[1] WL Observed	Number of Observations	Radium-226[2] pCi/l	Number of Observations
Aluminum	-	-	13.0	3
Antimony	.91	1	-	-
Copper[3]	.70	2	6.7	9
Gold[4]	.20	4	81.7	1
Iron[5]	.48	5	16.7	1
Lead/Zinc[6]	.37	12	(6.46)[7]	5
Molybdenum	.83	3	15.8	1
Nickel	-	-	8.34	1
Silver	.24	2	4.47	1
Tungsten	.61	2	-	-
Vanadium	-	-	(2.44)[8]	1

(1) Underground operation, Goodwin, MSHA, written communication, 1978; (2) Calspan Corporation, 1975, (3) Includes a copper and silver mine; (4) Includes a gold and silver mine; (5) Includes a magnetite mine; (6) Includes 3 zinc only mines, 3 lead only mines and a lead/silver mine; (7) Less than 1 pCi/l replaced with .5 pCi/l in calculation; (8) Composite of two samples.

TABLE 5. SUMMARY OF RADIOLOGICAL INFORMATION ON NONMETALLIC COMMODITIES GIVEN IN APPENDIX B

Commodity	Average Maximum* WL Observed	Number of Observations
Clay	0.3	5
Fluorspar	1.2	3
Gypsum	0.30	1
Limestone	0.16	1
Phosphate	1.6	1
Silica Sand	0.19	1
Talc	(0.18)**	1

* Underground operation, Goodwin, MSHA, written communication, 1978

** Average WL, maximum value not available